PHILOSOPHICAL
TRANSACTIONS A

royalsocietypublishing.org/journal/rsta

Opinion piece

Check for
updates

Cite this article: Cohen IJ, Rymer AM. 2020 Cross-NASA divisional relevance of an Ice Giant mission. *Phil. Trans. R. Soc. A* **378**: 20200222.
http://dx.doi.org/10.1098/rsta.2020.0222

Accepted: 4 August 2020

One contribution of 18 to a discussion meeting issue 'Future exploration of ice giant systems'.

Subject Areas:
space exploration, solar system

Keywords:
Ice Giants, Uranus and Neptune, robotic space exploration, cross-disciplinary space science, future missions, NASA science

Author for correspondence:
Ian J. Cohen
e-mail: ian.cohen@jhuapl.edu

THE ROYAL SOCIETY
PUBLISHING

Cross-NASA divisional relevance of an Ice Giant mission

Ian J. Cohen and Abigal M. Rymer

The Johns Hopkins University Applied Physics Laboratory,
11000 Johns Hopkins Road, Laurel, MD 20723, USA

IJC, 0000-0002-9163-6009; AMR, 0000-0002-4879-0748

Robotic space exploration to the outer solar system is difficult and expensive and the space science community works inventively and collaboratively to maximize the scientific return of missions. A mission to either of our solar system Ice Giants, Uranus and Neptune, will provide numerous opportunities to address high-level science objectives relevant to multiple disciplines and deliberate cross-disciplinary mission planning should ideally be woven in from the start. In this review, we recount past successes as well as (NASA-focused) challenges in performing cross-disciplinary science from robotic space exploration missions and detail the opportunities for broad-reaching science objectives from potential future missions to the Ice Giants.

This article is part of a discussion meeting issue 'Future exploration of ice giant systems'.

1. Introduction

Robotic space exploration presents unbridled opportunities to expand human understanding of the natural order of our planet, our solar system, our universe and beyond. Large-scale missions comprise more than just ground-breaking science [1], they also fuel innovation, public engagement and global partnership in ways that few other endeavours can. Deep-space missions that venture into the outer solar system—such as Galileo at Jupiter, Cassini at Saturn and, it is hoped, soon future missions to the Ice Giant planets of Uranus and Neptune—advance astrophysics, planetary science, solar system studies, sociology (e.g. studying team dynamics through multigenerational missions), philosophy and beyond. To truly facilitate this scope of influence and capability requires collaborations that transcend boundaries that sometimes exist due to tradition or funding lines.

NASA funding of robotic space missions comes from the Science Mission Directorate (SMD) and is predominantly supported by one of four divisions: Astrophysics, Earth Science, Heliophysics or Planetary Science. Astrophysics focuses on the origin of the universe and extra-solar system celestial bodies and structures (stars, galaxies, supernovae etc.); Earth Science on interconnected terrestrial processes including weather, atmospheric dynamics, geophysics, hydrology and climate change; Heliophysics on solar and space plasma physics, including space weather, planetary magnetospheric dynamics and aeronomy, and the interaction of our solar system with the local interstellar medium (LISM); and Planetary Science on the formation and characterization of all planetary bodies (from the smallest to the largest) within our solar system and beyond. Obviously, there are large overlaps and synergies across the Divisions. Our emerging expertise in studying exoplanets (planets orbiting stars besides our own), for example, is spear-headed by Astrophysics (remote sensing of exoplanets with large space-based telescopes) with needed expertise also shared across Planetary Science (characterization of exoplanets in the context of the worlds in our own solar system) and Heliophysics (characterization of planet-stellar wind interactions in our habitable astrosphere).

The Divisions within NASA's SMD fund missions and programs based on strategic and/or Congressionally-directed programs as outlined by implementation plans, strategic plans and science plans that are regularly updated at both the SMD and Division levels. The respective science communities outline their priorities in the form of 'Decadal Survey' reports administered by the National Academy of Sciences. These Decadal Surveys, generated with broad community input, occur every 10 years and outline the successes, challenges and future vision within each discipline, as defined by the community. The Decadal Surveys are key cornerstones for the community that define the field's vision for the near-term future; however, while they provide references for NASA (and the National Science Foundation), and policymakers, they are *not* guiding documents, nor are the Divisions bound (nor at times able) to follow them completely. Though this review focuses primarily on NASA and the funding processes within the USA, it should be noted that the Science Programme at ESA is likewise guided by community-driven long-term plans that occur roughly each decade and place high value in cross-disciplinary themes [2]. Furthermore, it should be emphasized that most major future space exploration missions (not just those to the Ice Giants) will benefit greatly from shared opportunities and coordination between international agencies, which generally have similar or complementary strategic science goals.

In this review, we recount past successes as well as challenges in performing cross-disciplinary science from robotic space exploration missions and specifically detail the opportunities for broad-reaching science objectives from potential future missions to the Ice Giants.

2. Past successes for cross-disciplinary science

Perhaps the greatest example of cross-divisional science from a robotic mission comes from the Voyager mission. Voyager's 'Grand Tour' of the outer solar system was borne of the realization of a once-in-a-lifetime cosmic alignment of the outer planets in the late twentieth century (figure 1). With the ambitious aim to successfully rendezvous with all four of the Giant planets, the dual Voyager spacecraft (hereafter denoted as 'V1' and 'V2') were simultaneous developed in the 1970s and instrumented with a comprehensive payload that included both *in situ* and remote sensing instrumentation (figure 2) [3]. The *in situ* payload included particle and fields instruments, such as the plasma experiment (PLS), magnetometer (MAG), the cosmic ray investigation (CRS), the low-energy charged particle experiment (LECP) and the plasma wave sensors (PWS). The remote sensing payload included, the imaging experiment (ISS), the infrared spectroscopy and radiometry experiment (IRIS), the planetary radio astronomy experiment (PRA), the ultraviolet spectrometer experiment (UVS) and the photopolarimeter (PPS), as well as the radio science investigation (RSS). Together this payload, duplicated on both Voyager spacecraft, revealed early

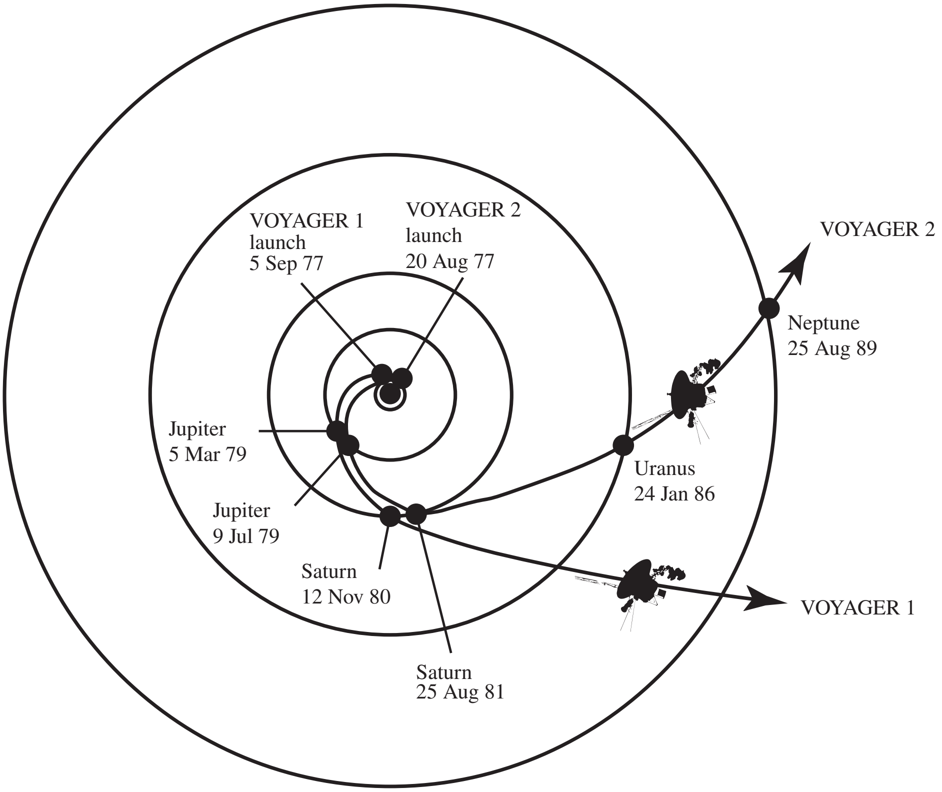

Figure 1. The Voyager Mission, which visited all of the Giant planets, was an ambitious endeavour and became an exemplar of what cross-disciplinary missions could achieve. Credit: NASA/JPL.

(and for the Ice Giants, the only) views of the Giant planets: Jupiter from V1 [4] and V2 [5], Saturn from V1 [6] and V2 [7], Uranus from V2 [8] and Neptune from V2 [9]. V2 also put the solar system into new perspective by capturing the solar system's family portrait and the famous 'Pale Blue Dot' image of Earth (figure 3).

Because V1 and V2 planned close flybys of Titan at Saturn and Triton at Neptune, respectively, they left the ecliptic plane as they careened beyond their final planetary targets: V1's trajectory bent northward (or above) the ecliptic and V2 headed southward (or below). Since both Voyager spacecraft were already outfitted with the necessary *in situ* instrumentation, these diverging trajectories presented a unique opportunity for the Heliophysics and Astrophysics communities: a chance to sample the outer limits of the solar system and its interface with the interstellar medium for the first time and from two spatially removed vantage points. Thus, on 1 January 1990, the Voyager Mission ended and the Voyager Interstellar Mission (VIM) officially began [10]. Because of the changed nature of the mission, only seven of the original 11 instruments were kept powered on: all of the particles and fields instruments, as well as the PRA and UVS. These intrepid explorers yet again boldly went where no spacecraft had gone before, becoming humankind's first interstellar explorers and providing our first (and to-date only) *in situ* observations of our solar system's termination shock [11], heliopause, heliosheath [12] and LISM [13].

Other missions have made similar transitions beyond their original mission objectives and gone on to contribute significant additional cross-disciplinary science in addition to their primary missions. The lunar reconnaissance orbiter (LRO) was conceived as part of NASA's New Vision for Space Exploration [14]. The mission launched in 2009 with an initial 1-year Exploration Mission focused on supporting the expansion of human exploration throughout the solar system and under the responsibility of the directorate now known as the Human Exploration and

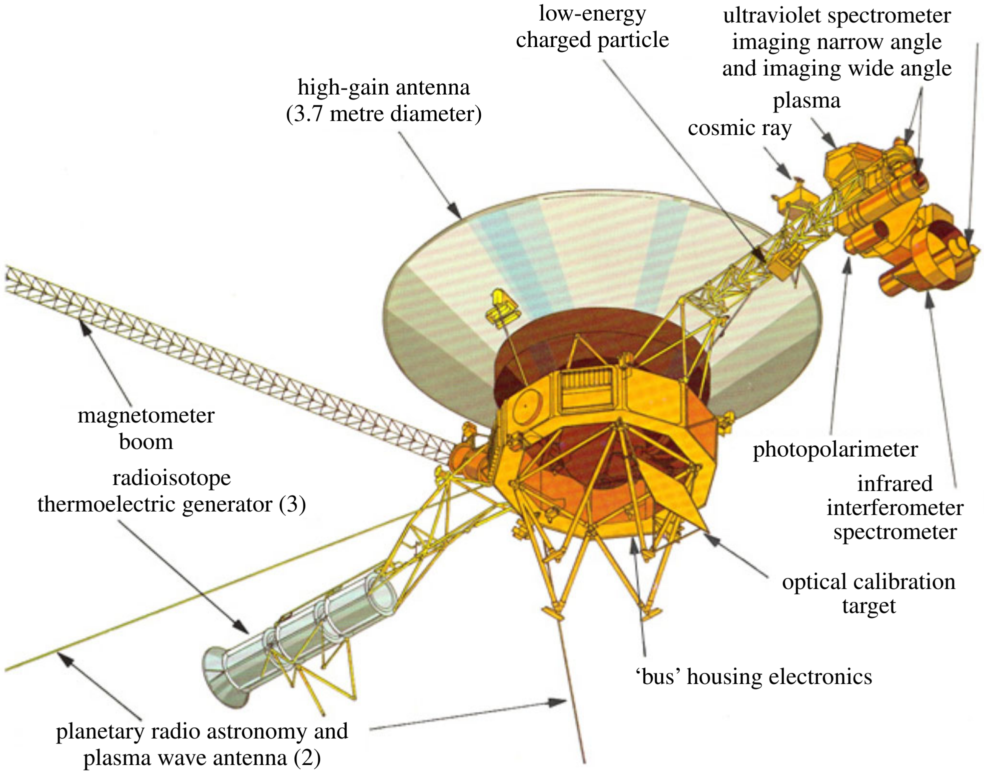

Figure 2. Voyager's ability to provide revolutionary Heliophysics and Astrophysics measurements from beyond the solar system was enabled by its comprehensive *in situ* and remote sensing payload. Credit: NASA/JPL. (Online version in colour.)

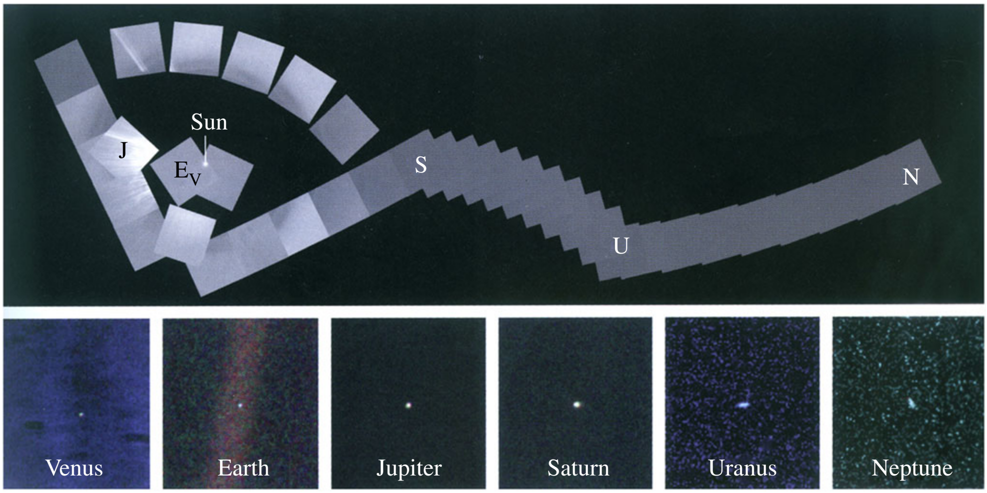

Figure 3. Voyager's visits to the Gas Giants provided humanity its first views of the Gas Giants, and put Earth and the other planets into cosmic perspective. Image credit: NASA/JPL-Caltech. (Online version in colour.)

Operations Mission Directorate [15]. After completion of this Exploration Mission, responsibility for LRO was transferred to SMD's Planetary Science Division, where it has provided a wealth of lunar science [16]. Similarly, the Deep Impact mission to comet Tempel 1 (9P/Tempel) [17] first completed its prime mission of achieving and observing a hypervelocity impact with a comet [18] and then found a second life as the EPOXI mission, encountering comet Hartley 2 (103P/Hartley

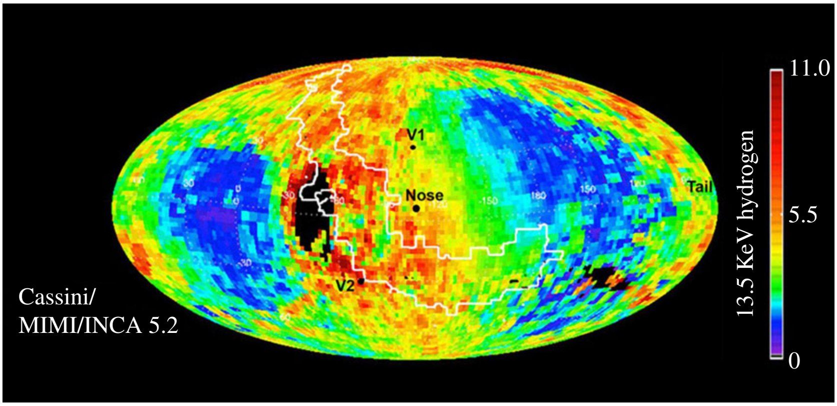

Figure 4. Though not initially part of its proposed objectives, the Cassini/INCA instrument was able to image the heliospheric boundary during the cruise to Saturn. These maps suggest a closed, 'bubble-like' shape to the heliosphere, which contrast with the conclusions from the IBEX missions; the issue remains hotly debated in the heliophysics community today. Image credit: NASA/JPL/JHUAPL. (Online version in colour.)

2) [19] and exploring exoplanets [20]. Finally, the Wide-field Infrared Survey Explorer (WISE) mission was an astrophysics mission originally intended to complete a mid-infrared survey of the entire sky [21], but has since provided a wealth of observations of asteroids and near-Earth objects as the NEOWISE mission [22].

A notable example of fortuitous cross-disciplinary science comes in the form of energetic neutral atom imaging—a technique that has quite recently been used, with remarkable results, to map the outermost edges of our Sun's astrosphere. The Interstellar Boundary Explorer (IBEX) mission was launched in 2008 with the goal to map the heliospheric boundary to better understand the nature of the solar system's interaction with the LISM and provide global context to the localized *in situ* measurements from the VIM [23]; though funded by the Heliophysics Division, the science goals of IBEX are cross-disciplinary and of interest to both the Heliophysics and Astrophysics communities.

Soon after the launch of IBEX, further heliospheric imaging contributions came from an unlikely source: the Ion and Neutral Camera (INCA) [24] on the Cassini spacecraft en route to Saturn [25]. INCA's initial science objective was to '[d]etermine the global configuration and dynamics of hot plasma in the magnetosphere of Saturn through energetic neutral particle imaging of ring current, radiation belts and neutral clouds' [24]. However, during its cruise to Saturn from 2003 to 2009 INCA obtained images of the heliospheric boundary at energies not covered by the IBEX instrumentation (figure 4) [26]. Beyond providing an additional dataset, the Cassini/INCA observations provided evidence that the heliosphere is closed (i.e. a 'bubble') [26,27], which directly contradicted the conclusions from the IBEX observations that the heliosphere is open (i.e. has a comet-like tail) [28,29]. The debate between these two models rages on in the Heliophysics community, with hopes that it will be resolved by the upcoming Interstellar Mapping and Acceleration Probe (IMAP) mission, a Heliophysics Division-funded mission that carries updated versions of both the IBEX and Cassini/INCA instruments [30].

NASA missions have demonstrated many examples of cross-Divisional observations over the years. Cassini flybys of both Venus and Earth in 1999 [31] provided unique measurements of these planets, including the first detection of thermal emission from the Venusian surface at 0.85 and 0.9 µm [32], the escape of energetic neutral atoms from Venus' atmosphere [33], resolution of a low energy beam in the plasmasheet [34] and potential measurements of Earth's magnetotail as far away as 6000 R_E [35]. Most recently, the Parker Solar Probe mission [36] completed several of its planned flybys of Venus as it dives closer into the Sun's corona [37].

Several missions have made use of Jupiter gravity assists and in doing so, provided additional measurements of the Jovian system. For instance, the Ulysses (solar physics mission) flyby of

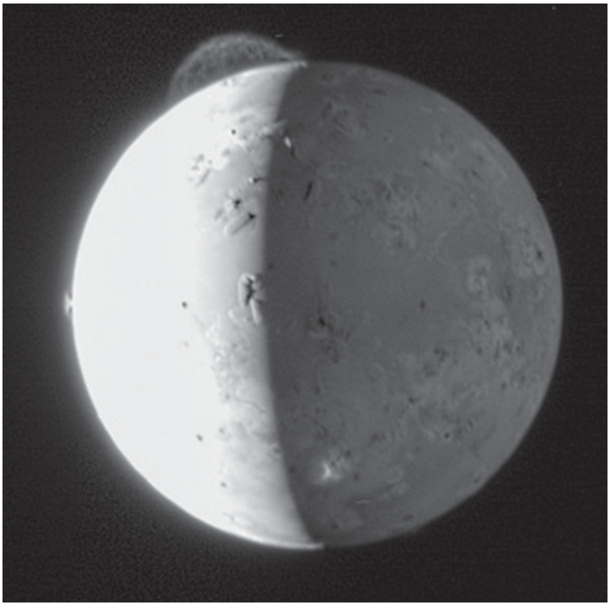

Figure 5. Flybys not only provide beneficial gravity assists but also additional scientific opportunities at secondary targets that can provide unexpected results, like this image of Tvashtar erupting on Io captured by New Horizons flyby of Jupiter while en route to Pluto. Image credit: NASA/JHUAPL/SwRI.

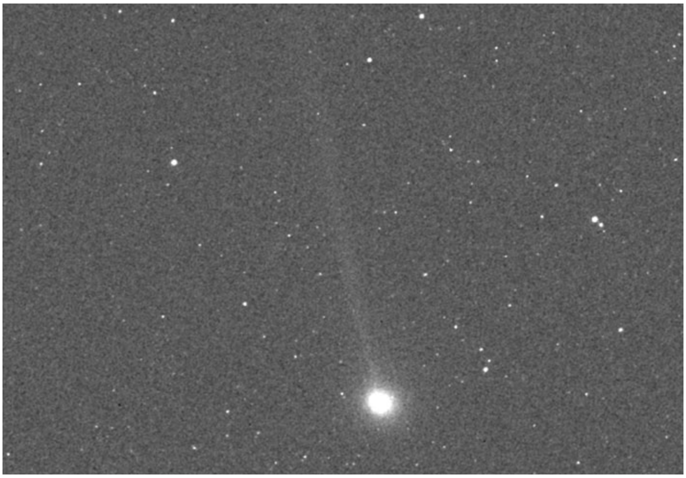

Figure 6. Several missions have had opportunities to make serendipitous observations of comets, like this image of 2P/Encke from the MESSENGER mission to Mercury. Image credit: NASA/JHUAPL/CIW.

Jupiter accessed previously un-investigated regions of the planet's magnetosphere, including higher magnetospheric latitudes, the dusk sector and inner magnetosphere [38]. Similarly, New Horizons [39] flyby flew down Jupiter's enormous (extending all the way to Saturn's orbit) magnetotail and observed escaping plasmoids [40]. Both Ulysses and New Horizons also revealed evidence of volcanic activity on Io [41,42], with the latter capturing the impressive eruption of the volcano Tvashtar (figure 5).

Chance encounters have also provided opportunistic scientific observations for missions carrying appropriate instrumentation. For example, MESSENGER (mission to Mercury) [43] unexpectedly obtained images and spectra of comets 2P/Encke (figure 6) and C/2012 S1 (ISON).

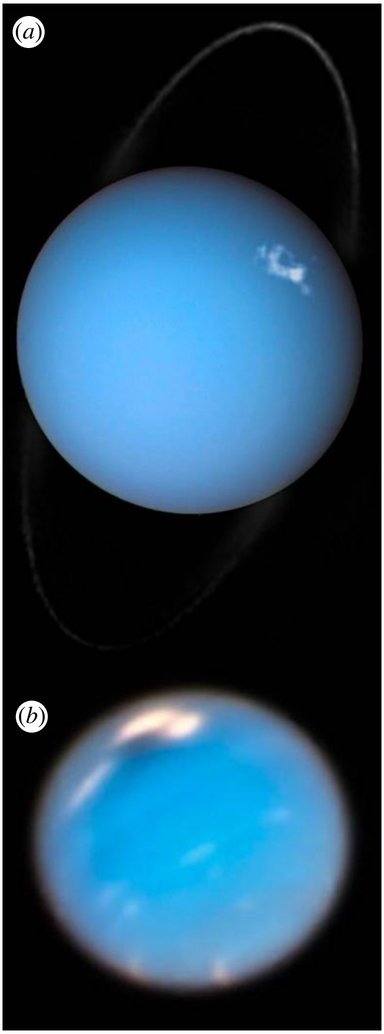

Figure 7. Dedicated campaigns by the Hubble Space Telescope have made significant contributions to planetary science, including capturing aurora on Uranus (*a*) and the evolution of large storms on Neptune (*b*). Image credits: ESA/Hubble & NASA, L. Lamy/Obs. De Paris; NASA/ESA/GSFC/JPL. (Online version in colour.)

The Sun-focused Ulysses mission also captured *in situ* observations of multiple comet tails [44,45] as well as contributing to a catalogue of gamma-ray bursts from throughout the universe along with Near Earth Asteroid Rendezvous (NEAR; asteroid mission), Wind (solar wind mission) and Compton Gamma Ray Observatory (CGRO; astrophysics) [46].

Long cruise durations on the way to planetary targets, especially those in the outer solar system often provide ample opportunities to acquire additional observations, like the previously discussed heliospheric energetic neutral atom images from Cassini/INCA. Voyager and many later planetary missions (e.g. Pioneer Venus, Galileo, Cassini and MESSENGER) obtained UV measurements of interplanetary hydrogen [47] and were also able to contribute to astrophysical studies via stellar occultations [48] during cruise. Many missions, like New Horizons, have also made significant studies of solar wind [49], pick-up ionization [50] and interplanetary shock [51] evolution throughout the outer solar system.

Finally, Earth-based astrophysics space assets also provide invaluable cross-disciplinary measurements. For instance, the Hubble Space Telescope (HST) has provided a rich legacy of solar system observations, including giant planet images captured as part of the Outer Planets

Atmospheres Legacy (OPAL) program [52]. HST images have revealed many features of the Giant planets, such as the auroral footprints from the Galilean moons at Jupiter [53], the dynamics of the rings and auroral storms at Saturn [54], auroral emissions at Uranus (figure 7*a*) [55] and the development of large storms at Neptune (figure 7*b*) [56]. HST was also able to capture the approach, impact and aftereffects of the 2009 impact of the Shoemaker-Levy 9 comet [57] and both the Spitzer Space Telescope [58,59] and Chandra X-ray Observatory [60–63] had robust programs of solar system observations.

3. Challenges

These recollections of the missions that transcended their scope are by no means comprehensive. While such a cogent collection of successes could make the achievement of cross-disciplinary science seem like a routine or easy occurrence, there are significant challenges to realizing such cross-disciplinary science opportunities that all of these successful cross-disciplinary missions have had to navigate. There are several approaches that NASA (and other space agencies such as ESA and JAXA) and the broad scientific community can adopt to help towards the goal of creating and successfully capitalizing on more cross-disciplinary science opportunities in the future: increasingly facilitate and encourage healthy communication both across focused scientific communities and vertically between the leadership and staff at the respective space agencies and NASA Divisions; all members of all of scientific communities are able to actively advocate for cross-disciplinary opportunities and investigations via, for example, white papers to the respective Decadal Surveys, and by proposing cross-disciplinary science investigations by leveraging the existing infrastructure for funding (e.g. technology demonstration opportunities, rideshares, missions of opportunity, etc.). Most importantly the opportunity for cross-disciplinary science needs to be *recognized* and purposefully planned, where feasible while remaining cognizant of the current fiscal realities. As our review has hopefully demonstrated, a lot of these previous opportunities were not even conceived of until after mission launch; cross-disciplinary opportunities conceived early in mission development will likely yield the strongest return on enhancing cross-disciplinary science.

4. Cross-disciplinary science opportunities from a future Ice Giant Mission

The Ice Giants, as the least explored and least well-understood planets in our solar system, leave a gaping hole in the completeness of our survey of potential planetary regimes. Future missions to the Ice Giants offer prime opportunities for cross-disciplinary science and can benefit from lessons learned on previous missions, such as those discussed above.

A decade-long (or longer) cruise to either Ice Giant would provide an opportunity to study the evolution of the solar wind, acceleration processes and interplanetary shocks with radial distance from the sun. Understanding the evolution and variability of these is important for understanding stars and star–planet interactions, and thus informs not only heliophysics and planetary science, but astrophysics and exoplanetary research as well. Likewise, valuable observations of interstellar and interplanetary dust throughout the outer solar system could be obtained, building on the results of New Horizons [64], Cassini [65], Ulysses [66] and others. Acquiring energetic neutral atom images of the heliospheric boundary, as Cassini did, from the outermost regions of the solar system could provide the long baselines needed to achieve useful stereoscopic imaging of targets; images from Uranus (20 AU) or Neptune (30 AU) obtained concurrently with those from Jupiter (5 AU) and/or Earth (1 AU) could provide 3D mapping of the heliospheric boundary that could perhaps provide important constraints in the debate over the shape of the heliosphere. A long cruise would also provide many years for opportunities to obtain ultraviolet spectra of interplanetary hydrogen and distant stars via occultations. Visible, infrared and radio measurements of the sun and stars could also be obtained via occultations. Imagers or spectrometers with sufficient resolution from the distant outer solar system could continue the search for new Kuiper Belt objects (as New Horizons did) and/or exoplanets. They could also perhaps observe the planets of our solar system as exoplanets would be [67] and could help further put the worlds we know into the context of the ever-expanding catalogue of known exoplanets [68]. The exploration of the Ice Giants is intrinsically beneficial to exoplanetary science because understanding all the planetary types we have access to (which may be only a small sampling of the diversity of exoplanets that exist) helps to bound the characteristics of exoplanetary systems.

Future missions to the Ice Giants also provide opportunities to investigate additional targets, like Cassini, New Horizons, Ulysses and other predecessors, these missions would likely provide a wealth of information from measurements obtained while performing a flyby to obtain a gravity assist at another planet (likely Jupiter, Earth, Venus and/or Saturn). Those observations may be even more advantageous if timelines align such that they happen to occur simultaneously with other missions at the same target, e.g. with Europa Clipper or JUICE in the Jovian system. Such extended solar system trajectories could also provide chance encounters with comets, like MESSENGER and Ulysses experienced.

While such cross-disciplinary objectives could largely be met with instruments that already have high value for Ice Giant exploration [57–59], the opportunity to augment the baseline payload with additional instruments (perhaps with funding from other Divisions or international partners) could further expand the science return of future missions.

5. Conclusion

Robotic space exploration, especially to the outer solar system, is by its very nature difficult and expensive. As such, it behoves the entire space science community to work collaboratively to maximize the scientific return of missions, regardless of the primary discipline or funding source. NASA and partner international space agencies have consistently navigated these challenges and provided many lessons, both positive and cautionary, that can be learned from previous missions that have successfully bridged traditional disciplinary boundaries.

In particular, future missions to the Ice Giants at the outer reaches of the solar system can provide many opportunities for cross-disciplinary science, especially if they are purposefully planned for early on in the development of the missions. In particular, long interplanetary cruise phases and opportunities to access infrequently visited regions of the solar system beyond 10 AU should not be squandered. *In situ* particle and fields measurements advance our understanding of the evolution of the solar wind throughout the solar system, and remote sensing instruments provide unique vantage points of the heliosphere and the planets within it. Our future missions to the Ice Giants not only address outstanding questions about planetary and exoplanetary systems but also offer the chance to achieve even more far-reaching science objectives if we are willing to strive for them.

Data accessibility. This article has no additional data.

Authors' contributions. I.J.C. and A.M.R. both contributed equally to the construction and delivery of the prose presented in this article.

Competing interests. We declare we have no competing interests.

Funding. This work was funded via internal investment by The Johns Hopkins University Applied Physics Laboratory Civil Space Mission Area.

Acknowledgements. We authors thank The Royal Society as well as L. Fletcher (Univ. of Leicester) and the rest of the Organizing Committee of the 'Future exploration of the ice Giants' discussion meeting, where an invited presentation on this topic was presented. Much thanks is also extended to R. Vervack, R. McNutt, J. Westlake, M. Gkioulidou, A. Higginson, K. Mandt, P. Kollmann and G. Clark from JHU/APL for very fruitful discussions that led to the contents of that presentation and this paper.

References

1. Hammel HB. 2020 Lessons learned from (and since) the Voyager 2 flybys of Uranus and Neptune. *Phil. Trans. R. Soc. A* **378**, 20190485. (doi:10.1098/rsta.2019.0485)

2. European Space Agency. 2005 *Cosmic vision: space science for Europe 2015–20257*, pp. 111. ESA Brochure, BR-24.
3. Kohlhase CE, Penzo PA. 1977 Voyager mission description. *Space Sci. Rev.* **21**, 77–101. (doi:10.1007/BF00200846)
4. Stone EC, Lane AL. 1979 Voyager 1 encounter with the Jovian system. *Science* **204**, 945–948. (doi:10.1126/science.204.4396.945.1979a)
5. Stone EC, Lane AL. 1979 Voyager 2 encounter with the Jovian system. *Science* **206**, 925–927. (doi:10.1126/science.204.4396.945)
6. Stone EC, Miner ED. 1981 Voyager 1 encounter with the Saturnian system. *Science* **212**, 159–163. (doi:10.1126/science.212.4491.159)
7. Stone EC, Miner ED. 1982 Voyager 2 encounter with the Saturnian system. *Science* **215**, 499–504. (doi:10.1126/science.215.4532.499)
8. Stone EC, Miner ED. 1986 Voyager 2 encounter with the Uranian system. *Science* **233**, 39–43. (doi:10.1126/science.233.4759.39)
9. Stone EC, Miner ED. 1989 Voyager 2 encounter with the Neptunian system. *Science* **246**, 1417–1421. (doi:10.1126/science.246.4936.1417)
10. Rudd RP, Hall JC, Spradlin GL. 1997 The Voyager Interstellar Mission. *Acta Astronaut.* **40**, 383-396. (doi:10.1016/s0094-5765(97)00146-x)
11. Decker R *et al.* 2008 Mediation of the solar wind termination shock by non-thermal ions. *Nature* **454**, 67–70. (doi:10.1038/nature07030)
12. Stone EC *et al.* 2005 Voyager 1 explores the termination shock region and the Heliosheath beyond. *Science* **309**, 2017–2020. (doi:10.1126/10.1126/science.1117684.2005)
13. Strauss RDT. 2019 Voyager 2 enters interstellar space. *Nat. Astron.* **3**, 963–964. (doi:10.1038/s41550-019-0942-5)
14. NASA. 2004 *The Vision for Space Exploration*, NP-2004–01-334-hq.
15. Vondrak R *et al.* 2010 Lunar reconnaissance orbiter (LRO): observations for lunar exploration and science. *Space Sci. Rev.* **150**, 7–22. (doi:10.1007/s11214-010-9631-5)
16. Robinson M, Overst J. 2018 LRO: seven years exploring the Moon. *Planet. Space Sci.* **162**, 1. (doi:10.1016/j.pss.2018.09.008)
17. A'Hearn MF *et al.* 2005 Deep impact: a large-scale active experiment on a cometary nucleus. *Space Sci. Rev.* **117**, 1–21. (doi:10.1007/s11214-005-3387-3)
18. A'Hearn MF *et al.* 2005 Deep impact: excavating Comet Tempel 1. *Science* **310**, 258–264. (doi:10.1126/science.1118923)
19. A'Hearn MF *et al.* 2011 EPOXI at comet Hartley 2. *Science* **332**, 1396–1400. (doi:10.1126/science.1204054)
20. Christiansen JL *et al.* 2010 Studying the atmosphere of the exoplanet HAT-P-7b via secondary eclipse measurements with *EPOXI*, *SPITZER*, and *KEPLER*. *ApJ* **710**, 97. (doi:10.1088/0004-637X/710/1/97)
21. Wright EL *et al.* 2010 The wide-field infrared survey explorer (wise): mission description and initial on-orbit performance. *ApJ*, **140**, 6. (doi:10.1088/0004-6256/140/6/1868)
22. Mainzer A *et al.* 2011 Preliminary results from neowise: an enhancement to the *wide-field infrared survey explorer* for solar system science. *ApJ* **731**, 1. (doi:10.1088/0004-637X/731/1/53)
23. McComas DJ *et al.* 2009 IBEX—Interstellar Boundary Explorer. *Space Sci. Rev.* **146**, 11–33. (doi:10.1007/s11214-009-9499-4)
24. Krimigis SM *et al.* 2004 Magnetosphere Imaging Instrument (MIMI) on the Cassini Mission to Saturn/Titan. *Space Sci. Rev.* **114**, 233–329. (doi:10.1007/s11214-004-1410-8)
25. Matson DL, Spilker LJ, Lebreton J. 2002 The Cassini/Huygens Mission to the Saturnian System. *Space Sci. Rev.* **104**, 1–58. (doi:10.1023/A:1023609211620)
26. Krimigis SM *et al.* 2009 Imaging the Interaction of the Heliosphere with the Interstellar Medium from Saturn with Cassini. *Science* **326**, 971–973. (doi:10.1126/science.1181079)
27. Dialynas K *et al.* 2017 The bubble-like shape of the heliosphere observed by Voyager and Cassini. *Nat. Astron.* **1**, 0115. (doi:10.1038/s41550-017-0115)
28. McComas DJ *et al.* 2009 Global observations of the Interstellar Interaction from the Interstellar Boundary Explorer (IBEX). *Science* **326**, 959–962. (doi:10.1126/science.1180906)
29. McComas DJ *et al.* 2013 The Heliotail revealed by the Interstellar Bondary Explorer. *Astrophys. J.* **771**, 2. (doi:10.1088/0004-637X/771/2/77)

30. McComas DJ *et al.* 2018 Interstellar Mapping and Acceleration Probe (IMAP): a new NASA Mission. *Space Sci. Rev.* **214**, 116. (doi:10.1007/s11214-018-0550-1)
31. Burton ME, Buratti B, Matson DL, Lebreton J-P. 2001 The Cassini/Huygens Venus and Earth flybys: an overview of operations and results. *J. Geophys. Res.* **106**, 30 099–30 107. (doi:10.1029/2001JA900088)
32. Baines KH *et al.* 2000 Detection of sub-micron radiation from the surface of Venus by Cassini/VIMS. *Icarus* **148**, 307–311. (doi:10.1006/icar.2000.6519)
33. Krimigis SM, Mitchell DG, Hamilton DH, Livi S, Dandouras J. 1999 Preliminary results from MIMI observations during Cassini/ Huygens's Venus-2 Flyby on June 24, 1999. *Bull. Am. Astron. Soc.* **3**, 4.
34. Rymer AM, Coates AJ, Svenes K, Abel GA, Linder DR, Narheim B, Thomsen M, Young DT. 2001 Cassini Plasma Spectrometer Electron Spectrometer measurements during the Earth swing-by on August 18, 1999. *J. Geophys. Res.* **106**, 30 177–30 198. (doi:10.1029/2001JA900087)
35. Lagg A, Krupp N, Livi S, Woch J, Krimigis SM, Dougherty MK. 2001 Energetic particle measurements during the Earth swing-by of the Cassini spacecraft in August 1999. *J. Geophys. Res.* **106**, 30 209–30 222. (doi:10.1029/2001JA900048)
36. Fox NJ *et al.* 2016 The Solar Probe Plus Mission: Humanity's First Visit to Our Star. *Space Sci. Rev.* **204**, 7–48. (doi:10.1007/s11214-015-0211-6)
37. Curry S *et al.* 2019 Parker Solar Probe observations of the first Venus flyby. In Presentation SM51A-09 at the 2019 AGU Fall Meeting, San Francisco, CA, 13 December 2019.
38. Smith EJ, Wenzel K-P, Page DE. 1992 Ulysses atr Jupiter: an overview of the encounter. *Science* **257**, 1503–1507. (doi:10.1126/science.257.5076.1503)
39. Stern SA. 2008 The new horizons Pluto Kuiper belt mission: an overview with historical context. *Space Sci. Rev.* **140**, 3–21. (doi:10.1007/s11214-007-9295-y)
40. McComas DJ, Allegrini F, Bagenal F, Crary F, Ebert RW, Elliott H, Stern A, Valek P. 2007 Diverse plasma populations and structures in Jupiter's magnetotail. *Science* **318**, 217–220. (doi:10.1126/science.1147393)
41. Spencer JR, Howell RR, Clark BE, Klassen DR, O'connor D. 1992 Volcanic activity on Io at the time of the Ulysses encounter. *Science* **257**, 1507–1510. (doi:10.1126/science.257.5076.1507)
42. Spencer JR *et al.* 2007 Ion volcanism seen by New Horizons: a major eruption of the Tvashtar Volcano. *Science* **318**, 240–243. (doi:10.1126/science.1147621)
43. Solomon SC *et al.* 2007 MESSENGER mission overview. *Space Sci. Rev.* **131**, 3–39. (doi:10.1007/s11214-007-9247-6)
44. Neugebauer M *et al.* 2007 Encounter of the Ulysses Spacecraft with the Ion Tail of Comet McNaught. *Astrophys. J.* **667**, 1262–1266. (doi:10.1086/521019)
45. Snow M *et al.* 2004 Comet Hyakutake (C/1996 B2): spectacular disconnection event and the latitudinal structure of the solar wind. *Planet. Space Sci.* **52**, 313–323. (doi:10.1016/j.pss.2003.10.001)
46. Hurley K *et al.* 2011 The interplanetary network supplement to the burst and transient source experiment 5B catalog of cosmic gamma-ray bursts. *Astrophys. J. Supp. Series* **196**, 1. (doi:10.1088/0067-0049/196/1/1)
47. Quemerais E *et al.* 1995 A new source of Lyα emission detected by Voyager UVS: heliospheric or galactic origin? *Astron. Astrophys.* **299**, 249.
48. Holberg JB, Ali B, Carone TE, Polidan RS. 1991 Absolute far-ultraviolet specrophotometry of hot subluminous stars from voyager. *Astrophys. J.* **11**, 33–36. (doi:10.1016/0273-1177(91)90056-P)
49. Elliott HA *et al.* 2016 The New Horizons Solar Wind Around Pluto (SAWP) observations of the solar wind from 11–33 AU. *Astrophys. J.* **223**, 2. (doi:10.3847/0067-0049/223/2/19)
50. Randol BM, McComas DJ, Schwadron NA. 2013 Interstellar pick-up ions observed between 11 and 22 AU by New Horizons. *Astrophys. J.* **768**, 2. (doi:10.1088/0004-637X/768/2/120)
51. Zirnstein EJ *et al.* 2018 In situ observations of preferential pickup ion heating at an interplanetary shock. *Phys. Rev. Lett.* **121**, 075102. (doi:10.1103/PhysRevLett.121.075102)
52. Simon AA, Wong MH, Orton GS. 2015 First Results from the Hubble OPAL program: Jupiter in 2015. *Astrophys. J.* **812**, 1. (doi:10.1088/0004-637X/812/1/55)
53. Clarke J *et al.* 2002 Ultraviolet emissions from the magnetic footprints of Io, Ganymede and Europa on Jupiter. *Nature* **415**, 997–1000. (doi:10.1038/415997a)
54. Nichols JD *et al.* 2014 Dynamic auroral storms on Saturn as observed by the Hubble Space Telescope, *Geophys. Res. Lett.* **41**, 3323–3330. (doi:10.1002/2014GL060186)

55. Lamy L *et al.* 2012 Earth-based detection of Uranus' aurorae. *Geophys. Res. Lett.* **39**, L07105. (doi:10.1029/2012GL051312)
56. Simon AA, Wong MH, Hsu AI. 2019 Formation of a new Great Dark Spot on Neptune in 2018. *Geophys. Res. Lett.* **46**, 3108–3113. (doi:10.1029/2019GL081961)
57. Hammel HB *et al.* 1995 HST imaging of atmospheric phenomena created by the impact of comet Shoemaker-Levy 9. *Science* **267**, 1288–1296. (doi:10.1126/science.7871425)
58. Meadows VS *et al.* 2008 First Spitzer observations of Neptune: detection of new hydrocarbons. *Icarus* **197**, 585–589. (doi:10.1016/j.icarus.2008.05.023)
59. Verbiscer A, Skrutskie M, Hamilton D. 2009 Saturn's largest ring. *Nature* **461**, 1098–1100. (doi:10.1038/nature08515)
60. Snios B, Kharchenko V, Lisse CM, Wolk SJ, Dennerl K, Combi MR. 2016 Chandra observations of comets C/2012 S1 (ISON) and C/2011 L4 (PanSTARRS). *ApJ* **818**, 2. (doi:10.3847/0004-637X/818/2/199)
61. Branduardi-Raymont G *et al.* 2013 Search for Saturn's X-ray aurorae at the arrival of a solar wind shock. *J. Geophys. Res. Space Physics* **118**, 2145–2156. (doi:10.1002/jgra.50112)
62. Weigt DM *et al.* 2020 Chandra observations of Jupiter's X-ray auroral emission during Juno apojove 2017. *J.Geophys. Res. Planets* **125**, e2019JE006262. (doi:10.1029/2019JE006262)
63. Lisse CM *et al.* 2017 The puzzling detection of x-rays from Pluto by Chandra. *Icarus* **287**, 103–109. (doi:10.1016/j.icarus.2016.07.008)
64. Poppe A, James D, Jacobsmeyer B, Horányi M. 2010 First results from the Venetia Burney Student Dust Counter on the New Horizons mission. *Geophys. Res. Lett.* **37**, L11101. (doi:10.1029/2010GL043300)
65. Altobelli N *et al.* 2016 Flux and composition of interstellar dust at Saturn from Cassini's Cosmic Dust Analyzer. *Science* **352**, 312–318. (doi:10.1126/science.aac6397)
66. Krüger H *et al.* 2015 Sixteen years of Ulysses interstellar dust measurements in the solar system. I. Mass distribution and gas-to-dust ratio. *Astrophy. J.* **812**, 2. (doi:10.1088/0004-637X/812/2/139)
67. Crow CA *et al.* 2011 Views from EPOXI: colors in our solar system as an analog for extrasolar planets. *Astrophys. J.* **729**, 2. (doi:10.1088/0004-637X/729/2/130)
68. Bashi D, Helled R, Zucker S. 2018 A quantitative comparison of exoplanet catalogs. *Geosciences* **8**, 325. (doi:10.3390/geosciences8090325)